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CORNELL UNIVERSITY

Center for Radiophysics and Space Research

ITHACA, N. Y.

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T. Gold, E. Bilson, R. L. Baron

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April 1976

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ABSTRACT:

The dielectric constant and the voltage absorption length was measured for four Apollo 17 soil samples (73241, 74220, 75061, 76501) and for two Apollo 17 rock samples (76315 and 79135) at 450 MHz frequency. The dielectric constant and absorption length measurements made on all our lunar samples are reviewed and related to the transition element concentration in these samples. The significance of the laboratory measurements for radar observations is discussed.

INTRODUCTION

The dielectric constant, loss tangent, and d.c. conductivity of lunar samples have been studied by a number of research groups. Olhoeft and Strangway (1975) reviewed the dielectric constant and loss tangent values reported in the literature. The data cover both rock samples and fines from all the Apollo missions and represent measurements made, mostly at frequencies below 1 MHz, except for data by the present authors, obtained mostly at 450 MHz, and data by Bassett and Shackelford obtained at close to 10^{10} Hz. The temperature dependence of the dielectric properties has been studied between 78° K and approximately 500° K (Chung and Westphal (1973), Alvarez (1974) and Olhoeft et al. (1973)) and the frequency dependence has been examined over the range from 10^{2} to 10^{6} Hz (see the above references) with Katsube and Collett (1973) extending some measurements up to 1.8×10^{8} Hz. These studies have revealed the complexity of the dielectric properties of lunar materials. They show that the magnitude of the real component of the relative permittivity (usually called dielectric constant) is approximately independent of frequency, while the loss tangent is often a complex function of the frequency. Even at frequencies above 10^{6} Hz an extrapolation of the experimentally determined loss tangent values to higher frequencies is unreliable.

The prime purpose of our measurements has been the determination of the relevant dielectric properties of lunar material for the interpretation of the available radar studies of the Moon.

Since much radar information has been obtained at 68 cm wavelength, our measurements were made chiefly in this frequency range (450 MHz). In this paper we report our latest results characterizing Apollo 17 powder and rock samples. We also review our data of all the earlier Apollo missions, and we discuss the significance of the available radar information in the light of these data.

EXPERIMENTAL RESULTS

The measurements of the dielectric constant and loss tangent of rock and soil samples at 450 MHz were made by the methods described by Campbell and Ulrichs (1969). We determined the above quantities at several degrees of compaction (whenever possible) in the case of powder samples, in order to obtain information on their dependence on density. A theoretical density dependence curve was also generated for each measurement using the Rayleigh mixing formula (Campbell and Ulrichs (1969)). We estimate the accuracy of our determinations to be $\pm$3% for the dielectric constant and $\pm$10% for the loss tangent.

The sample handling techniques were the same for all the lunar samples examined. In order to avoid moisture effects the solid samples were cut dry in laboratory atmosphere and both solid and powder samples were baked in vacuum at 120° C for 2 days. Powder samples were stored in dessicators after the baking process. The measurements were made in air.

In our figures we display theoretical and experimentally determined density dependence of the dielectric constant and the voltage absorption length (expressed in wavelengths). The absorption length, $\ell_a = \frac{1}{\pi (k')^{1/2} \tan\delta}$, where k' is the real part of the relative permittivity or dielectric constant and $\tan\delta$ is the loss tangent. (We prefer to report absorption length values, instead of loss tangent data because of the more direct significance of the former for radar studies.)

Figure 1 shows the average dielectric constant vs. density Rayleigh curve for Apollo 17 soil samples-4 samples from different locations, including the orange soil, 74220-and data points for two Apollo 17 rock samples. This curve lies very close to the Apollo 11 and 12 curve, see Figure 2, which is included for comparison. The data points for the solid samples seem to be approximately on the extension to higher density of the powder Rayleigh curve. This is interesting because the Apollo 17 dust and rock samples display a great variety of chemical composition but for each rock type there is a corresponding dust type. This was not the case for example with the Apollo 11 and 12 samples and data points for the solid rocks did not fit the Rayleigh curve for dust.

Figure 3 shows the voltage absorption (i.e. the distance, expressed in terms of the wavelength, in which a signal will have its field-strength reduced to 1/e, or its power to $1/e^2$, a loss of 8.68 db) vs. density Rayleigh curves for Apollo 17

soil samples and data points for the rock samples. Again the solid data points lie close to the extension of Rayleigh curves representing dust of similar chemical composition as the rock. (Actually soil sample 75061 and rock sample 79135 are not as close mineralogically as indicated by the absorption curve.) Lunar rocks are generally much less absorbent than terrestrial ones. Rock 79135 is an example of one comparatively lossy solid lunar material, whereas the absorption in 76315 is less than in any terrestrial rock examined (Campbell and Ulrichs 1969).

Figure 4 shows, for comparison, voltage absorption vs. density Rayleigh curves for Apollo 11, 12, 14, 15 and 16 samples. The Apollo 17 samples display a greater range of absorbency than samples from any other Apollo missions. This observation is not unexpected if one considers the diversity in mineralogy and chemical composition of samples from the Apollo 17 site.

Table 1 lists the loss tangent values for all our lunar samples at 1 g/cm^3 density, calculated with the Rayleigh formula from the experimentally determined values at the actual density of the samples. In Table 1 we included loss tangent values, (normalized to the same density) as obtained by others for samples we have measured also. The few cases where there is substantial discrepancy in these loss tangent values may be attributable to the presence of a marked frequency dependence that may greatly change the absorptivity. Strangway et al. (1972) and Olhoeft et al. (1975) have examined the effect of adsorbed moisture on the dielectric properties of lunar samples.

They distinguish between a short term, reversible effect, occurring when samples otherwise kept in vacuum are brought up to an atmospheric pressure of air of 30% relative humidity, and a longterm, irreversible effect, occurring when samples are kept for months in air. While neither effect alters the dielectric constant more than tens of percent, just a short time (hours) exposure of samples to laboratory air can increase the loss tangent by as much as a factor of 50, at frequencies lower than 10^6 Hz. It is unclear however if the effect of moisture, adsorbed either during the handling of lunar samples from the first Apollo missions in the lunar receiving laboratory or during exposure of the samples to laboratory air during our measurements, is very significant at 450 MHz. Strangway et al. (1972) determined greatly different loss tangents for the powder sample 14163 in vacuum and in air below 10^4 Hz frequency but the results of vacuum and air measurements converged to become approximately the same above 10^5 Hz frequency. In fact, as Table 1 shows, the loss tangent data obtained in vacuum are in two cases a factor of 5-7 lower than ours whereas in one case a factor of 3 higher. Indeed it is not possible to make a detailed comparison of our results with others obtained at a different frequency. Moisture effects may be significant, but appear to be not very large at high frequencies. Our measurements might thus represent the upper limits of loss tangent values of the different samples and therefore the lower limits of the absorption lengths. The range of loss tangent values extrapolated to 1 g/cm^3 density is 0.017 (rock sample 12063) — 0.00055 (rock sample 15597) in our determinations and 0.054

(rock sample 12022) — 0.00007 (rock sample 60015) as reported in the literature.

DISCUSSION

The most significant observation emerging from the review of the dielectric properties of lunar material is the great range of absorbency, expecially in the case of rock samples. Whereas some iron rich Apollo 11 and 12 rocks are as absorbent as the average terrestrial rocks, a number of lunar rocks, especially anorthosites, are much less absorbent than any rock samples on the Earth. Since dust samples are usually mixtures of different minerals, the range of absorbency is smaller in these samples, however quite low loss tangent values are also exhibited by the majority of these samples, and especially those from the Apollo 15 and 16 missions.

In Figure 5 we plotted the absorption length, at 1.6 g/cm^3 density, in our samples as a function of the concentration of iron + titanium in these samples. A linear relationship between the logarithm of the absorption length and the iron + titanium content is indicated. At a given density and frequency the chemical composition and especially the transition metal content seems to be the determining factor in the dielectric absorption properties of lunar material. Such a conclusion was also drawn by Olhoeft and Strangway (1975). These authors however observed some clustering of the loss tangent data, such as samples from the earlier missions had higher loss tangents than those from the more recent missions, possibly due to moisture contamination effects. Such a clustering is not obvious in our data.

Since we have measured the electrical properties of a representative series of samples from all the Apollo sites, always using the same experimental parameters and methods, and operating throughout under the same experimental conditions, our conclusions concerning the absorption properties are therefore not influenced by variations in the measurement techniques. It appears that lunar materials exhibit similar dependency on the concentration of transition metals both at radar frequencies and at the frequency of visible light, as indicated by our studies of the optical albedo of lunar soil and ground up rock samples (Gold et al., 1974 and 1975). Figure 6 shows the linear relationship between optical albedo and voltage absorption lengths in lunar soil samples. Whereas the optical albedo of the soil sample is related to both the bulk and surface iron and titanium concentration, and the low albedo of the soil seems to be related to the enrichment on the surface of soil grains in these elements, the absorption at radar frequencies seems only to be influenced by the bulk iron and titanium concentrations. As Figure 5 shows the data points of rock and dust samples fit the same curves.

In accord with Olhoeft and Strangway (1975) we have found no relation between the dielectric constant of our samples and their iron + titanium content. As these authors also found, the dielectric constant is mainly a function of density. Extrapolation of the average Rayleigh curve for all the powder samples to higher densities would predict the dielectric constant of most rock samples with reasonable accuracy as seen from Figure 2.

SIGNIFICANCE FOR RADAR OBSERVATIONS

The importance of these measurements for the interpretation of lunar radar data is evident. Thus if there existed crystalline rock (of dielectric constant similar to that observed for such samples) in large regions on the Moon, and with an overburden of soil thin compared with the absorption length (i.e. less than 50 or 100 meters for a radar wavelength of 7.5 meters, the wavelength at which the latest data are available, see Thompson, 1970) then a substantial reflection would result from this lower interface. If it were a rough surface (as compared to the radar wavelength), fractured by cratering events, it would result in a high signal level out to the lunar limb; the long-wave radar would display a Moon that is not limb-darkened, just as the optical appearance is not limb-darkened. A thin layer of powder over this rough reflecting surface would only deflect a small proportion of the power at the first interface, (7% at normal incidence and not more than 20% average over the Moon) and thus not affect the signal very much, except by the addition of the specular reflections from the sub-radar point, and the diminution of the reflection coefficient at the second interface. Under those circumstances the total power in the rough scatter component should be more than that in the central (specular, first surface) component. In fact it appears that there is extreme limb-darkening, the rough (diffuse) scatter component containing less than 5% of the central (specular) component

at a wavelength of 6.0 meters (Hagfors and Evans, 1968). This point is illustrated in Figure 7. Very much higher values of the radar absorbency of the soil than those reported here would need to be present over all radar resolved areas of the Moon, if a rough subsurface existed frequently at depths of a few meters only. Alternatively there may be a great depth of soil gradually compacting with depth, so that much of the absorption occurs before a rock interface is reached, or the lower interface would have to be smooth at the radar wavelength, precluding any substantial cratering. Either of these possibilities appear to be in conflict with the view that a shallow layer of powder overlies a crystalline bedrock, whose bombardment gave rise to the powder (Oberbeck and Quaide, 1973).

Acknowledgment

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Table 1

Sample		tanδ at $\rho=1 g/cm^3$	Frequency ($\times 10^6$ Hz)	Environment of determination	Reference
10084	soil	0.0062	450	air	Gold et al (1971)
10084	soil	0.0090	1	N_2	Katsube & Collett (1971
12063	rock	0.0170	450	air	Gold et al (1971)
12070	soil	0.0045	450	air	Gold et al (1971)
12070	soil	0.0144	1	N_2	Katsube & Collett (1971
14003	soil	0.0036	450	air	Gold et al (1972)
14163	soil	0.0036	450	air	Gold et al (1972)
14163	soil	0.0005	1	vacuum	Strangway et al (1972)
14163	soil	0.01	10^4	N_2	Bassett & Schackelford (1972)
14310	rock	0.0012	450	air	Gold et al (1972)
14310	rock	0.0070	1	N_2	Chung et al (1972)
14310	rock	0.0027	10^4	N_2	Bassett & Schackelford (1972)
15021	soil	0.0038	450	air	Gold et al (1973)
15041	soil	0.0033	450	air	ibid.
15081	soil	0.0030	450	air	ibid.
15211	soil	0.0029	450	air	ibid.
15221	soil	0.0018	450	air	ibid.
15301	soil	0.0027	450	air	ibid.
15301	soil	0.0005	1	vacuum	Olhoeft et al (1974)
15401	soil	0.0025	450	air	Gold et al (1973)
15498	rock	0.0027	450	air	ibid.
15597	rock	0.0006	450	air	ibid.
15601	soil	0.0012	450	air	ibid.
60017	rock	0.0008	450	air	ibid.
60025	rock	0.0006	450	air	this paper
60025	rock	0.0005	180	N_2	Katsube & Collett (1973
61500	soil	0.0024	450	air	Gold et al (1973)
62240	soil	0.0025	450	air	Gold et al (1973)
63501	soil	0.0017	450	air	ibid.
66041	soil	0.0024	450	air	ibid.
66041	soil	0.0017	180	N_2	Katsube & Collett (1973
67601	soil	0.0018	450	air	Gold et al (1973)

Table con't

68121	soil	0.0022	450	air	ibid.
73241	soil	0.0023	450	air	this paper
74220	soil	0.0046	450	air	this paper
74220	soil	0.0139	1	vacuum	Olhoeft et al (1973)
75061	soil	0.0085	450	air	this paper
76315	rock	0.0011	450	air	this paper
76501	soil	0.0038	450	air	this paper
79135	rock	0.0051	450	air	this paper

Figure Captions

Figure 1. Dielectric constant vs. density curve for Apollo 17 powder samples, obtained by averaging the Rayleigh curves corresponding to the experimental data points. Dielectric constant vs. density points for solid samples are also shown.

Figure 2. Dielectric constant vs. density curves for Apollo 11, 12, 14, 15 and 16 samples. Dielectric constant vs. density points are shown for solid samples from these missions.

Figure 3. The variation with density of the absorption length in Apollo 17 powder samples according to the Rayleigh formula. Absorption length vs. density data points for two solid samples are also shown.

Figure 4. The variation with density of the absorption length in Apollo 11, 12, 14, 15 and 16 samples. Absorption length vs. density data points are shown for solid samples from these missions.

Figure 5. The absorption length in soil and rock samples, calculated with the Rayleigh formula for 1.6 g/cm^3 density, vs. iron + titanium concentration in these samples. The bulk iron and titanium concentration was obtained in the literature as listed in Gold et al., (1975).

Figure 6. The absorption length in soil samples, calculated with the Rayleigh formula for 1.2 g/cm^3 density, vs. the optical albedo of these samples. The albedo was measured at 5500 Å wavelength, at 8° illumination angle and was normalized to MgO.

Figure 7. The relative radar echo power in function of the pulse delay time at a wavelength of 6.0 m as in Hagfors and Evans (1968). There is a direct relationship between the delay time and the angle which the radar ray makes to the normal to the (theoretically spherical) surface. The quasi specular and the diffuse component of the echo power are also indicated in the figure.

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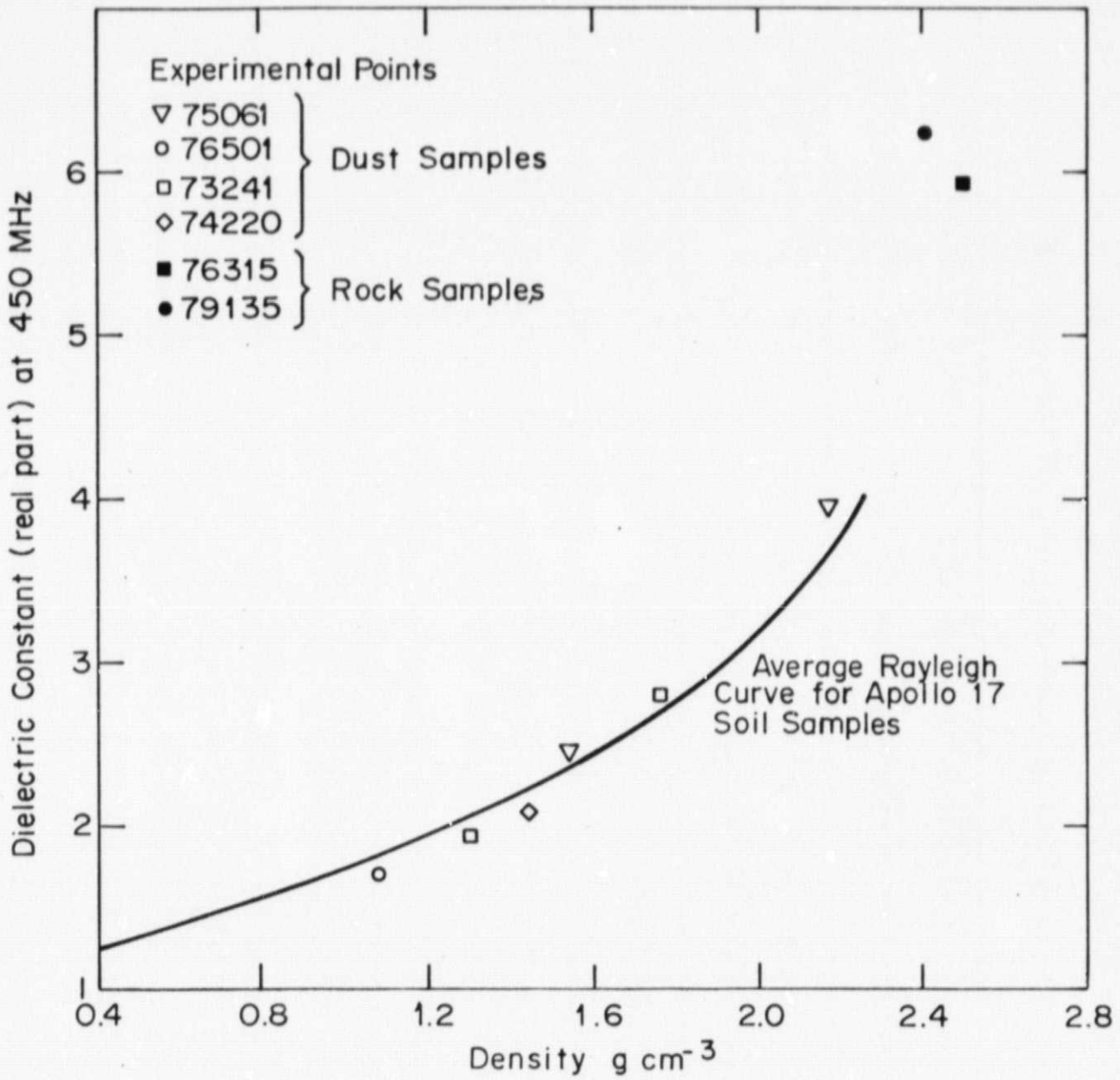
Experimental Points
▽ 75061
○ 76501
□ 73241
◇ 74220
Dust Samples
■ 76315
● 79135
Rock Samples
Average Rayleigh Curve for Apollo 17 Soil Samples
Dielectric Constant (real part) at 450 MHz
Density g cm⁻³
1
2
3
4
5
6
0.4
0.8
1.2
1.6
2.0
2.4
2.8

Figure 1

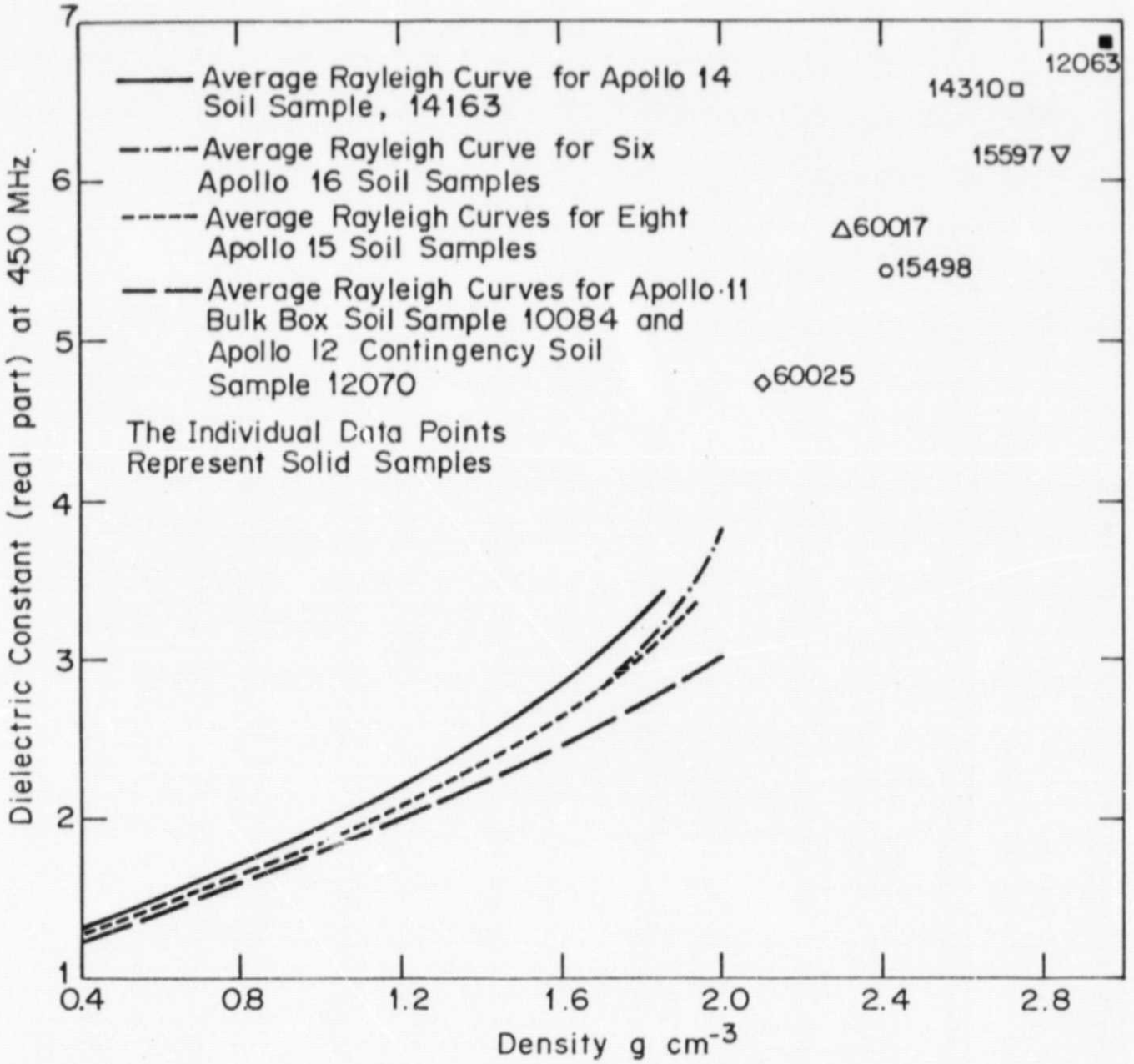
Average Rayleigh Curve for Apollo 14 Soil Sample, 14163
Average Rayleigh Curve for Six Apollo 16 Soil Samples
Average Rayleigh Curves for Eight Apollo 15 Soil Samples
Average Rayleigh Curves for Apollo 11 Bulk Box Soil Sample 10084 and Apollo 12 Contingency Soil Sample 12070
The Individual Data Points Represent Solid Samples
12063
14310
15597
60017
15498
60025
Dielectric Constant (real part) at 450 MHz.
Density g cm^{-3}
1
2
3
4
5
6
7
0.4
0.8
1.2
1.6
2.0
2.4
2.8

Figure 2

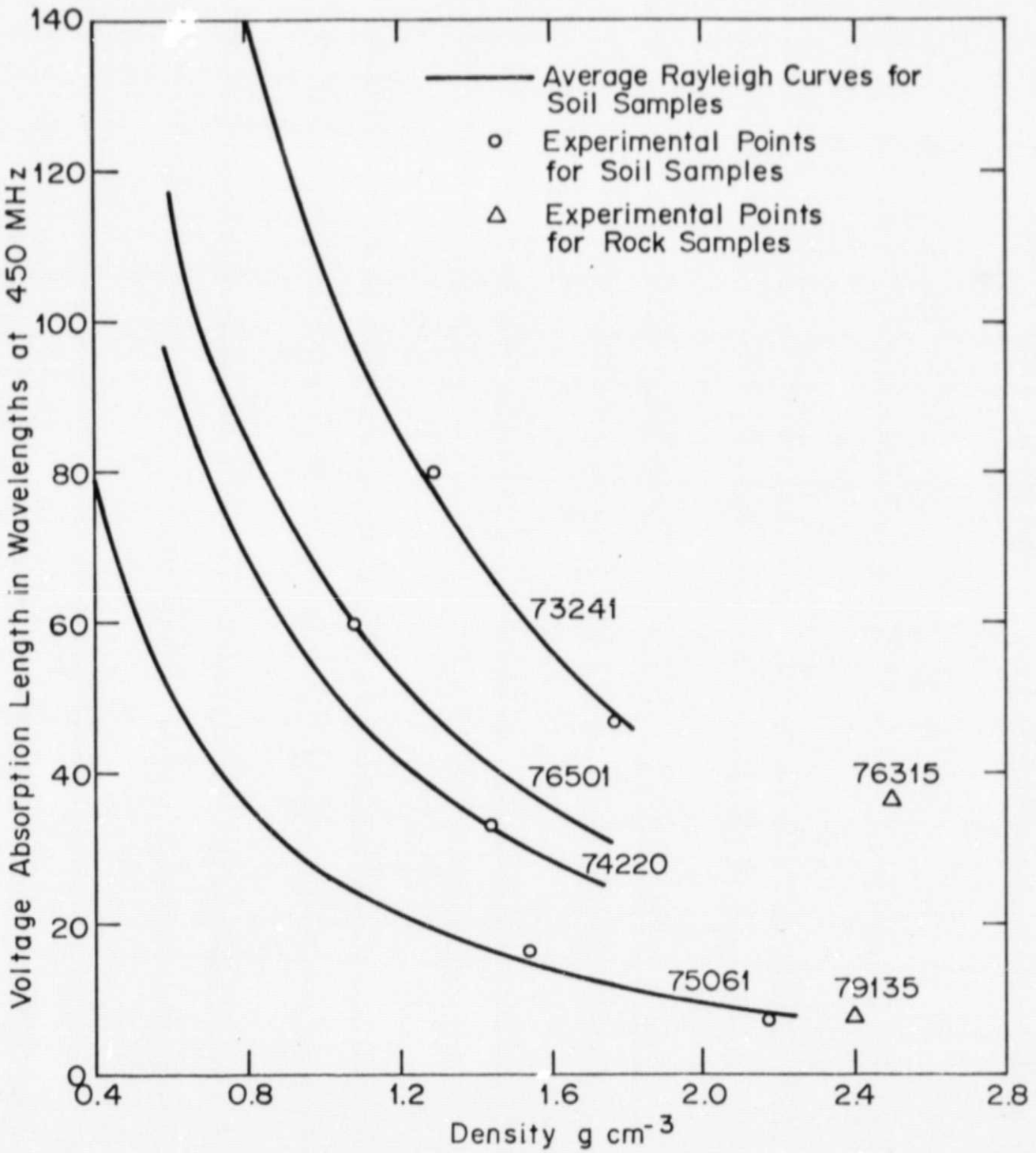
Average Rayleigh Curves for Soil Samples
Experimental Points for Soil Samples
Experimental Points for Rock Samples
73241
76501
74220
75061
76315
79135
Voltage Absorption Length in Wavelengths at 450 MHz
Density g cm⁻³
0
20
40
60
80
100
120
140
0.4
0.8
1.2
1.6
2.0
2.4
2.8

Figure 3

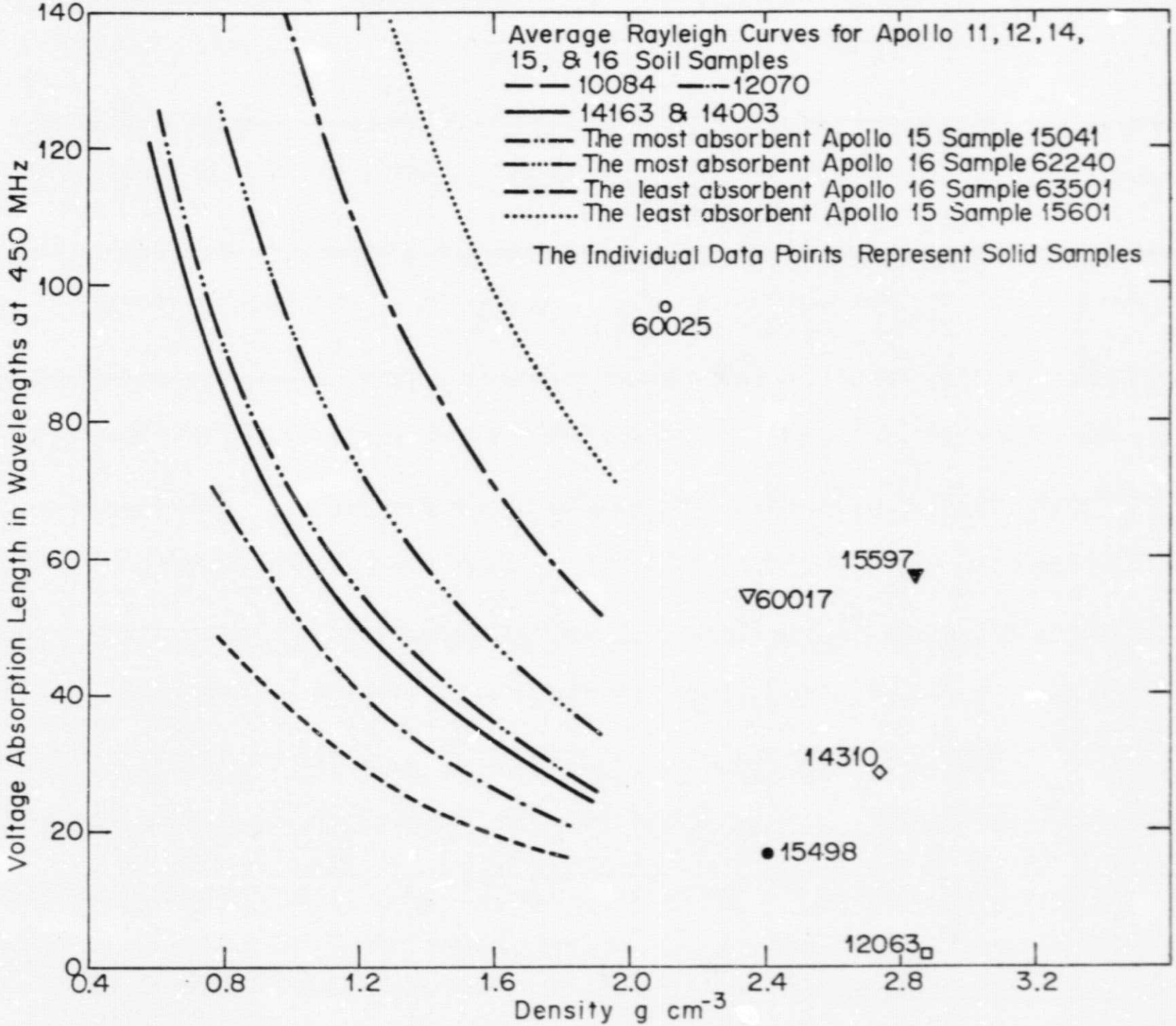
Average Rayleigh Curves for Apollo 11, 12, 14, 15, & 16 Soil Samples
10084
12070
14163 & 14003
The most absorbent Apollo 15 Sample 15041
The most absorbent Apollo 16 Sample 62240
The least absorbent Apollo 16 Sample 63501
The least absorbent Apollo 15 Sample 15601
The Individual Data Points Represent Solid Samples
60025
15597
60017
14310
15498
12063
Voltage Absorption Length in Wavelengths at 450 MHz
Density g cm-3
0
20
40
60
80
100
120
140
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2

Figure 4

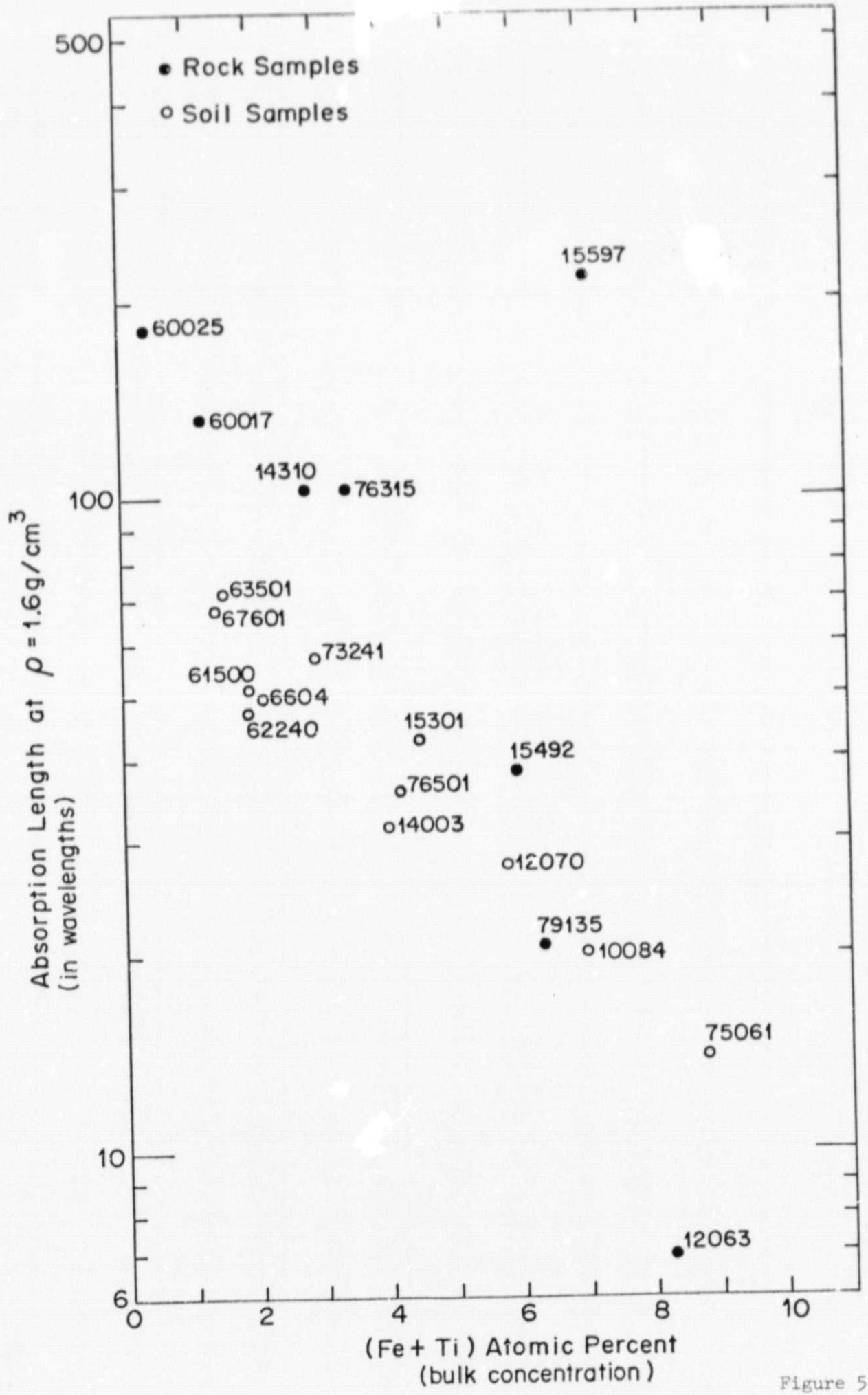
500
100
10
6
• Rock Samples
○ Soil Samples
15597
60025
60017
14310
76315
63501
67601
73241
61500
66604
62240
15301
15492
76501
14003
12070
79135
10084
75061
12063
Absorption Length at ρ = 1.6g/cm³
(in wavelengths)
0
2
4
6
8
10
(Fe + Ti) Atomic Percent
(bulk concentration)

Figure 5

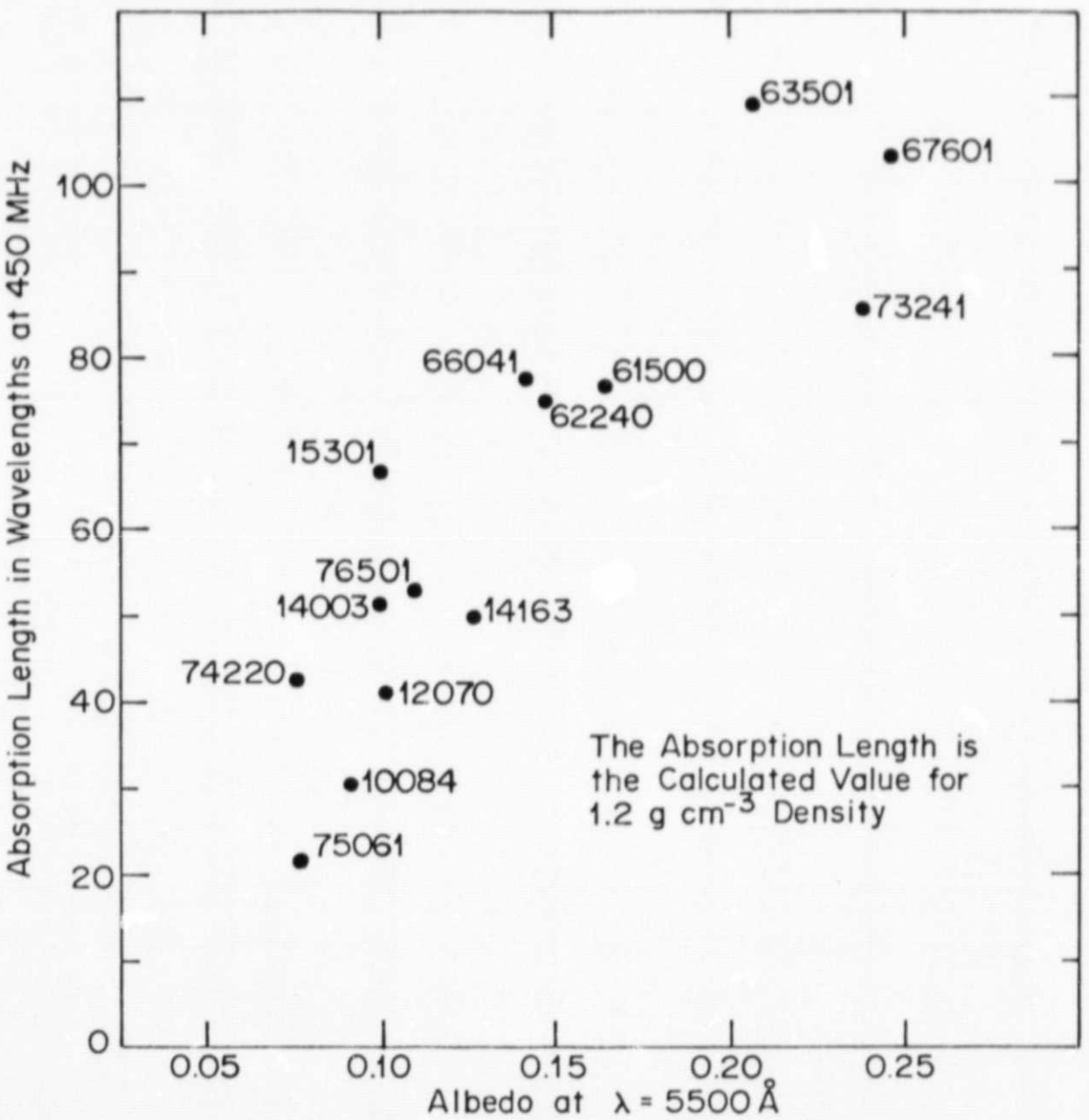
63501
67601
73241
66041
61500
62240
15301
76501
14003
14163
74220
12070
10084
75061
The Absorption Length is the Calculated Value for 1.2 g cm⁻³ Density
Absorption Length in Wavelengths at 450 MHz
0
20
40
60
80
100
0.05
0.10
0.15
0.20
0.25
Albedo at λ = 5500 Å

Figure 6

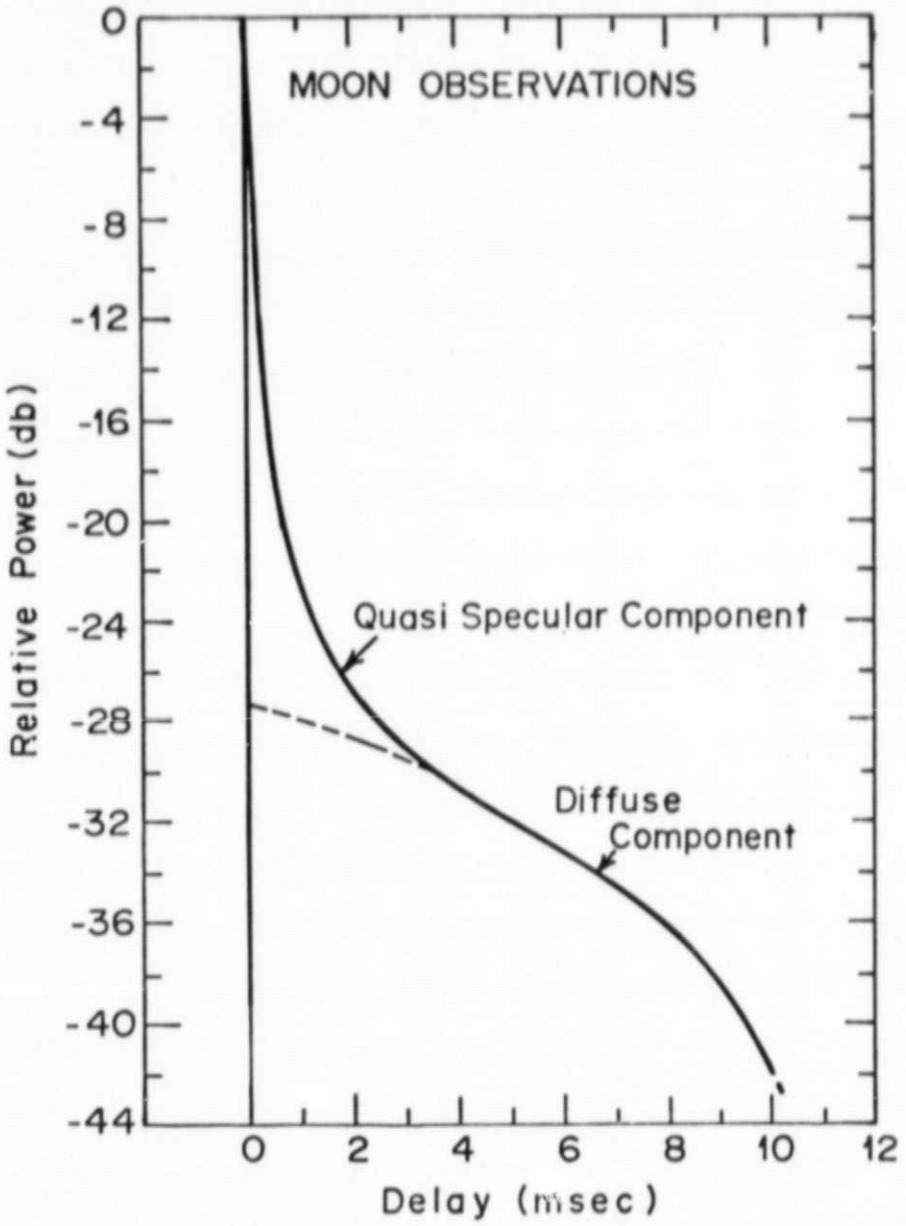
MOON OBSERVATIONS
Quasi Specular Component
Diffuse
Component
Relative Power (db)
0
-4
-8
-12
-16
-20
-24
-28
-32
-36
-40
-44
0
2
4
6
8
10
12
Delay (msec)

Figure 7